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Development of a Deployable Nonmetallic Boom for Reconfigurable Systems of Small Modular Spacecraft

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Abstract

Launch vehicle payload capacity and the launch environment represent two of the most operationally limiting constraints on space system mass, volume, and configuration. Large-scale space science and power platforms as well as transit vehicles have been proposed that greatly exceed single-launch capabilities. Reconfigurable systems launched as multiple small modular spacecraft with the ability to rendezvous, approach, mate, and conduct coordinated operations have the potential to make these designs feasible. A key characteristic of these proposed systems is their ability to assemble into desired geometric (spatial) configurations.

While flexible and sparse formations may be realized by groups of spacecraft flying in close proximity, flyers physically connected by active structural elements could continuously exchange power, fluids, and heat (via fluids). Configurations of small modular spacecraft temporarily linked together could be sustained as long as needed with minimal propellant use and reconfigured as often as needed over extended missions with changing requirements. For example, these vehicles could operate in extremely compact configurations during boost phases of a mission and then redeploy to generate power or communicate while coasting and upon reaching orbit.

In 2005, NASA funded Phase 1 of a program called Modular Reconfigurable High-Energy Technology Demonstrator Assembly Testbed (MRHE) to investigate reconfigurable systems of small spacecraft. The MRHE team was led by NASA's Marshall Space Flight Center and included Lockheed Martin's Advanced Technology Center (ATC) in Palo Alto and its subcontractor, ATK. One of the goals of Phase 1 was to develop an MRHE concept demonstration in a relevant 1-g environment to highlight a number of requisite technologies.

In Phase 1 of the MRHE program, Lockheed Martin devised and conducted an automated space system assembly demonstration featuring multipurpose free-floating robots representing spacecraft in the newly built Controls and Automation Laboratory (CAL) at the ATC. The CAL lab features a 12' x 24' granite air-bearing table and an overhead simulated starfield. Among the technologies needed for the concept demo were mating interfaces allowing the spacecraft to dock and deployable structures allowing for adjustable separation between spacecraft after a rigid connection had been established. The decision to use a nonmetallic deployable boom for this purpose was driven by the MRHE concept demo requirements reproduced in Table 1.

Table 1. MRHE Concept Demo Deployable Structure Requirements

Parameter	Value	Units
Number of Deploy/Stow Cycles	>100	none

Boom Bending Stiffness (EI)	400	Nm^2
Fully Deployed Length	2.0	meters
Transition Region Length	0.2	meters
Surface Finish	non-reflective	none
Deployment Speed	variable, up to 5	cm/sec
Deployment Mechanism	positive engagement drive, motorized deploy/retract	none

Deployable structures are so widely employed in spacecraft that a taxonomy may be developed. Bowden [1998] classifies the mechanisms broadly into hinged, linear, surface, and volume deployment devices. Deployable booms fall under linear deployment devices. They have been part of NASA's space exploration program since the development of the Viking Mars lander with its extending soil sampling arm. The STEM and BI-STEM [MacNaughton, 1967] have been commercially available for decades as off-the-shelf linear actuator modules for flight applications. Traditional deployable boom materials include stainless steel and BeCu but nonmetallic composite material booms have been built, as well [Del Campo, 1993]. Carbon fiber is attractive due to the high stiffness and strength to weight ratios that may be achieved and the material's versatility in production and fabrication techniques.

The deployable boom built for MRHE was the result of a joint effort in which ATK was primarily responsible for developing and fabricating the boom while Lockheed Martin designed and built the motorized Boom Deployment Mechanism (BDM) under a parallel but separate internal program. The three 2.5" diameter, 92" long booms delivered by ATK employ CRT (Collapsible Rollable Tube) technology (patent pending) developed by ATK for Lockheed Martin under an earlier, separate effort and refined (to generation CRT 2.5i) for MRHE. In Bowden's taxonomy, CRT booms fall somewhere between interlocking and lenticular booms in performance and complexity.

Figure 1 shows one of the MRHE booms in its lowest energy state (unrolled and unflattened). The boom is assembled from two halves consisting of 0.013" thick carbon fiber material joined by metal hinges and weighs approximately 0.003 lb/in, less than half the linear density of a metallic boom of comparable stiffness. Another benefit of the CRT boom is its ability to support torsional loads, a weakness of booms with simpler overlapping geometries. The boom end interfaces consist of a hole pattern matching the circular endcap supporting the docking probe of the mating interface on one end and holes lining up with the clamp on the BDM storage spool on the other end.

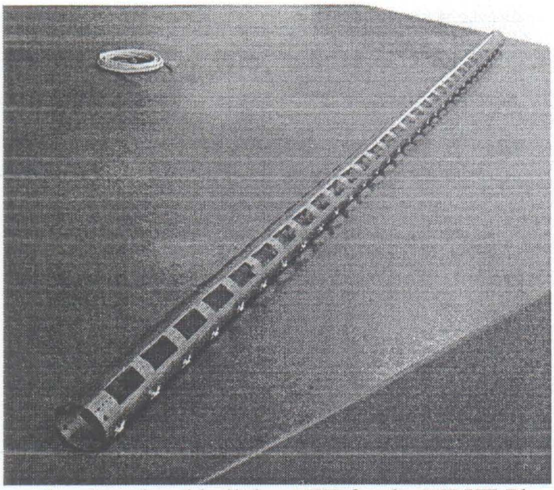

Figure 1. CRT 2.5i boom developed and built by ATK for the MRHE Phase 1 concept demo.

The goal of the CRT technology is to achieve a high-cycle deployable/retractable boom with a high packing ratio (≥10) and superior stiffness/weight characteristics throughout its deployable range. CRT enables controllable deployment including precision retraction and repeatability. The materials that make up CRT are fully processed on ground and do not go through any chemical changes or thermal plastic deformation during or after deployment. Function and repeatability of flight hardware can be demonstrated prior to final packaging.

A partially deployed CRT boom is fully rigid and can resist loads in any direction. The design and configuration of the structural components provide an open center geometry enhancing the flexibility of the structure in terms of different uses and applications for which the structure is suitable. In certain applications, electronic components may be integrated with the structural components of the deployable structural assemblies. Additionally, CRT is readily scalable to any length or cross-sectional size, exhibits low thermal distortion properties, good damping characteristics and a low amount of stored energy when in a stowed state.

CRT is made up of two hingedly coupled composite shells that form a structurally efficient member capable of simple deployment from a rolled state and retraction back to a rolled state. The discrete flex joints, or FlexHinge(TM), couple the two free edges of composite shells to form a tubular structure. Both the composite shells and flex joints fold flat allowing CRT to be compressed flat. Once flattened, CRT can be rolled onto a spool. The offsetting longerons on each composite shell allow CRT to stow with minimal strain. The design of the deployable structural assemblies enables simplified manufacturing of the structural components and provides considerable flexibility in the manufacturing and design process of such structural components.

The proposed paper will provide some background on CRT-1 and CRT-2a/b. Unlike these previous generations of CRT booms, the CRT 2.5i booms were built to fill the needs of the MRHE Phase 1 concept demo and not to characterize or push the limits of CRT technology. Exceeding the boom length requirement would not have benefited the program because the usable length was constrained by the limited maneuvering space available to the vehicles on the air-bearing table. In contrast, an 8.5 meter long CRT-1 boom was built for 1-g dynamic testing in a vertical orientation. However, the CRT technology is scaleable and lengths exceeding 100 m are feasible.

The BDM features a spring-loaded positive engagement drive, encoder-based position control, and end-of-travel/homing switches. Figure 2 shows the CRT boom (partially deployed, with a docking probe attached) and the BDM. The positive engagement drive helps to ensure that the boom stays centered on the rollers and does not walk off to one side or the other. It achieves this with toothed rollers that engage rows of drive holes along the boom longerons, similar to older computer printer paper feed mechanisms. Because the boom cannot slip when between the rollers, the deployed length can be accurately measured from deployment motor encoder counts.

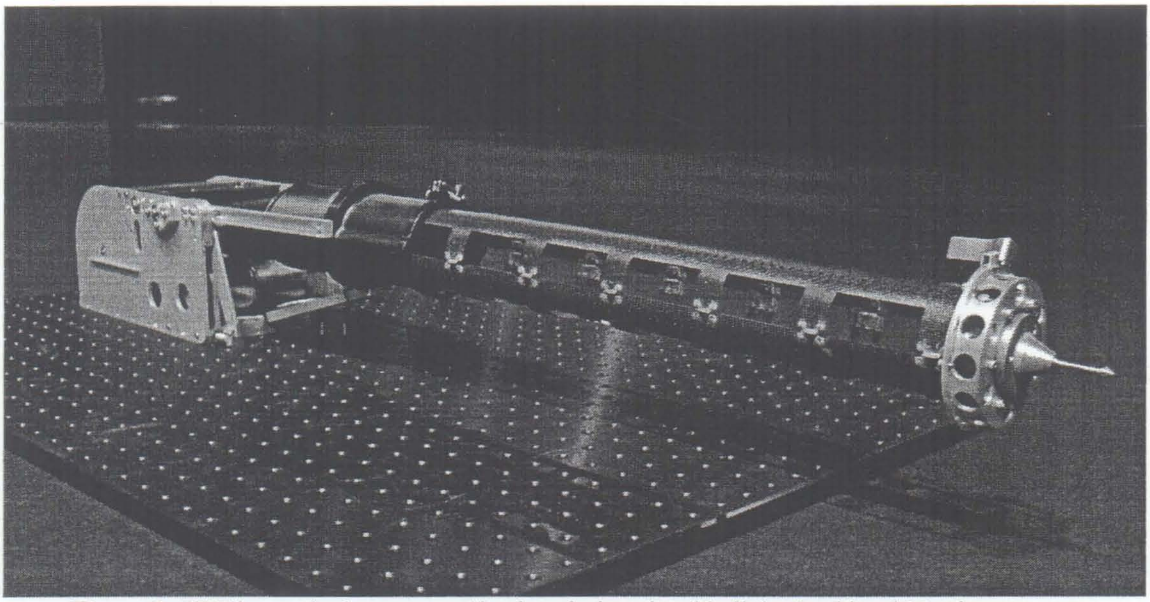

Figure 2. CRT boom deployment mechanism designed and built by Lockheed Martin.

A deployable length of 1.5 meters was sufficient for the purposes of the MRHE concept demonstration (see Figure 3) but subsequent efforts to decrease the fixed boom transition length (i.e., the distance between the feed rollers and circular support collar) have yielded 6 additional inches of deployable length in the same package, for a total deployable length of 65” (1.65 m).

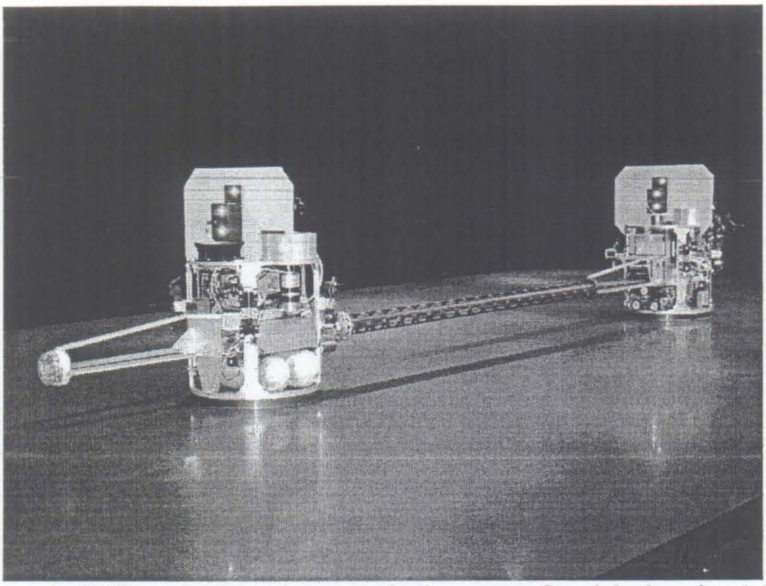

Figure 3. CRT boom connecting two robotic spacecraft and deployed to 1.5m.

The proposed paper will discuss the CRT and BDM designs in detail and present results from the vehicle integration and testing leading up to the MRHE concept demonstration. The boom stored energy calculations used to size the BDM retraction springs will also be discussed.

References

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